APPENDIX B: Seismology Report

Seismic Analysis of the Kean Canyon Explosion

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Abstract

An unfortunate industrial accident at a the Sierra Chemical Company plant east of Reno, Nevada, consisted of two explosions that occurred within about 3.5 *seconds* and were separated by $\approx$ 75 meters along a direction of S33°E (US Chemical Safety and Hazard Investigation Board). Using an high precision cross-correlation method applied to both seismic and air-waves recorded at several seismic stations in northern Nevada, we are able to resolve the relative locations, azimuth between the sources and the chronology of two explosions. The difference in moveout of air-waves between the two explosions, measured at several stations, associates the southern site with the second explosion. The separation of explosions, based on an analysis of these air-wave arrivals, at 3 stations is about 73 meters with an uncertainties ranging from ±7 to 21 meters. We obtained only a single estimate of source separation using P-waves which is 80 meters with a larger uncertainty of ±78 meters. We did a simultaneous determination of the separation and the azimuth of the explosions which combines the moveout at different stations. The best solution occurs with a separation of 73.2 meters with the second explosion occurring at azimuth of S35E from the first. These estimates are well within uncertainties of investigation by the US Chemical Safety and Hazard Investigation Board. From the relative spectral amplitudes of P- and air-waves, we suggest that explosion B had downward directivity, while A may have been more upwards directed. The corner frequency of the P-waves is much smaller than expected for the physical dimension of the explosions, indicating that attenuation is exerting a major influence on the P-wave spectrum at high frequency. The results from this analysis suggests that relative

location of small earthquakes with nearly identical seismograms can be achieved with similar accuracy using a regional seismic network.

Introduction

Two explosions occurred $\approx$3.5 *seconds* apart at the Sierra Chemical Company facility $\approx$20 km east of Reno, Nevada, on January 7, 1998. The events were heard and felt throughout the Reno-Sparks metropolitan area. Unfortunately, four people lost their lives and six more individuals were injured in the explosions. The recently organized United States Chemical Safety and Hazard Investigation Board (CSB), with the cooperation of several state agencies, initiated an investigation into the accident with the long range goal of improving the safety at explosive manufacturing facilities. An important aspect of the investigation was determining the chronology of events.

View of boooster room 1 following the explosion, with west wall still standing. The five workers in this room survived.

For More on CSB investigation see http://www.chemsafety.gov

The two explosions were recorded on several stations of the western Great Basin seismic network (Figure 1). From these records, the estimated origin time of the first explosion was 15:54:03.300. ±30*sec* GMT (7:54 AM PDT), with approximate location 39°North 31.8 minutes, 119°West 38.0 minutes. However, based on information provided by the CSB *(John Piatt, personal communication)* the location is 39°North 32.5 minutes, 119° West 38.1 minutes. We used the CSB's location in our subsequent analysis based on seismograms; it is well within normal uncertainties for earthquake locations. Treated as an earthquake, the magnitude of the event is estimated to be M$\approx$2.0. Four of the stations that recorded the explosion were recently installed digital broadband seismographs that were acquired through a grant to the University Nevada Reno from the Keck Foundation. Several of the seismograms are shown in Figure 2. The seismograms include two conspicuous P-wave arrivals, followed by an "N-wave" *(Kanamori et al., 1991)* that is created by the shock wave traveling in air. An examination of the seismograms (Figure 2) shows that there are two explosions separated in time by about 3.5 seconds. The phase that appears to be an S-wave in Figure 2 is the P-wave arrival from the second explosion, although there may be some amplitude contribution from an Lg phase. The station geometry relative to the source area is such that the P-wave arrival from the second source is nearly coincident with the expected Lg arrival from the initial event at both PAH and WCN. Evidence for the interpretation of these phase arrivals is based on the nearly same time separation observed in the air-wave arrivals at several stations. The larger amplitude of the P-wave and air-wave phases for the second event suggests that this was the larger of the two explosions, although the coupling of the explosion must also be taken into account in this interpretation.

Figure 1. Westert Nevada digital seismic stations, location of the chemical explosions and the Reno Sparks, and Carson City urban areas.

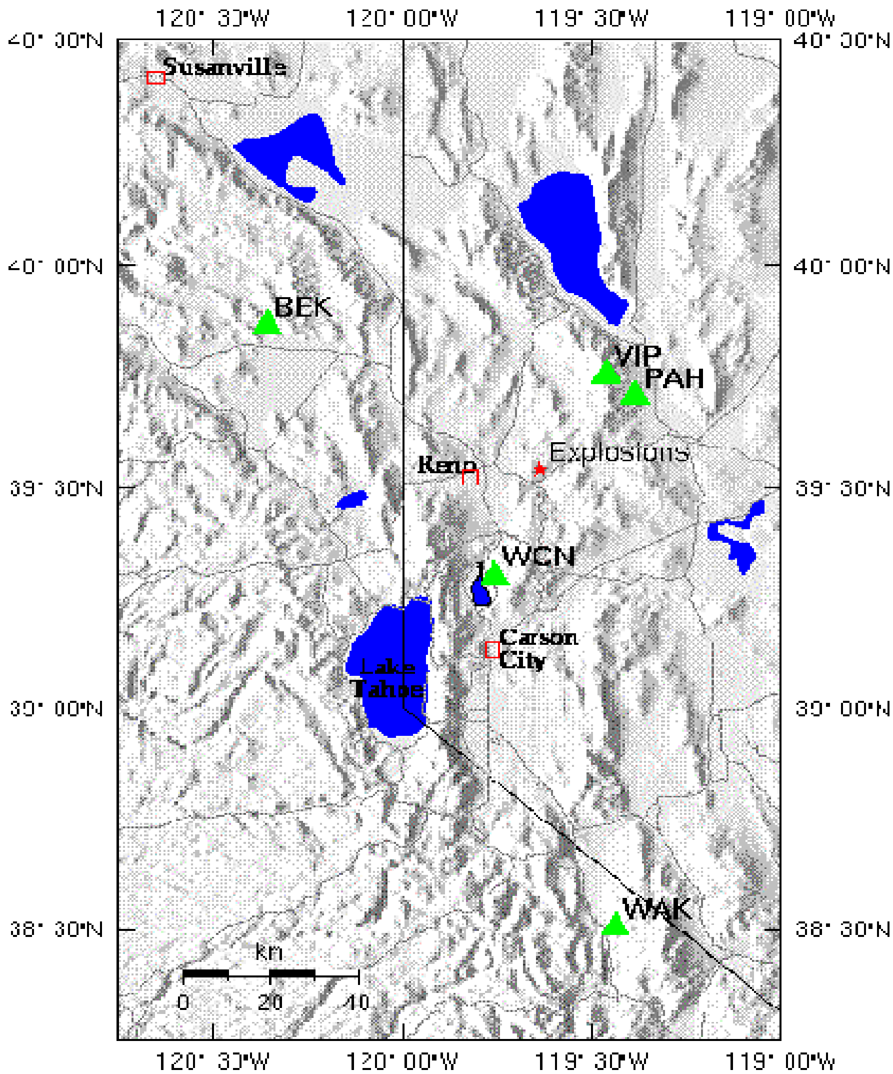


Table 1. Station locations, and their distances and azimuths to the estimated explosion site.

Code	Name	Latitude °N minutes	Longitude °W minutes	Elevation (km)	Distance (km)	Azimuth (°)
WCN	Washoe City, NV	39 18.10N	119 45.38W	1.50	28.6	201.5
VIP	Virginia Pk., NV	39 45.24N	119 27.65W	2.49	27.9	32.2
PAH	Pah Rah Range,NV	39 42.39N	119 23.05W	1.50	28.3	49.4
BEK	Bekwourth, CA	39 52.00N	120 21.52W	1.74	71.8	300.4
WAK	Walker, CA	38 30.26N	119 26.23W	1.89	116.3	171.5

Figure 2a.

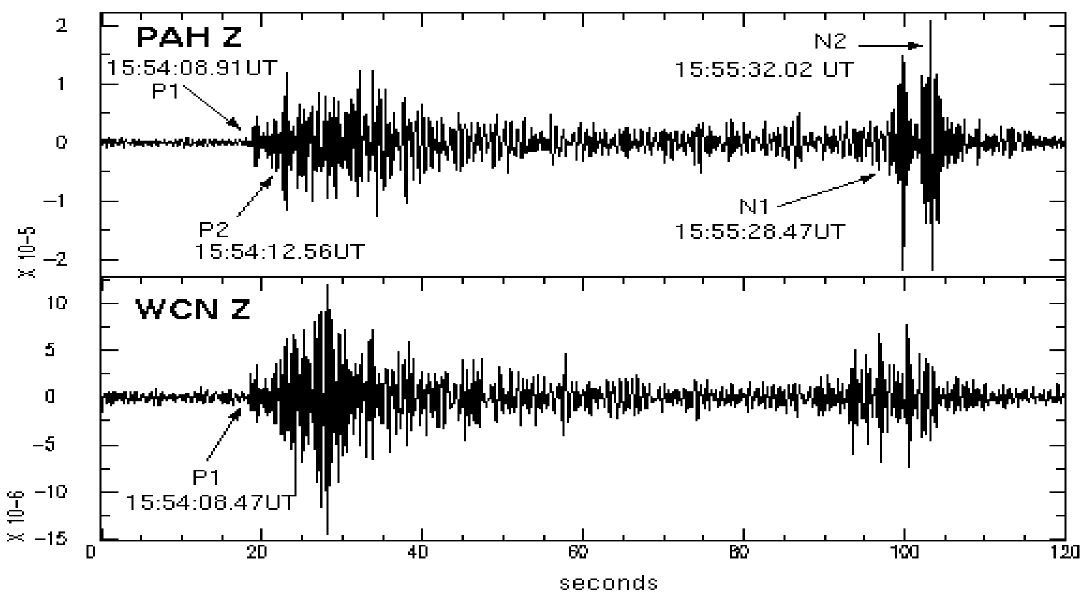
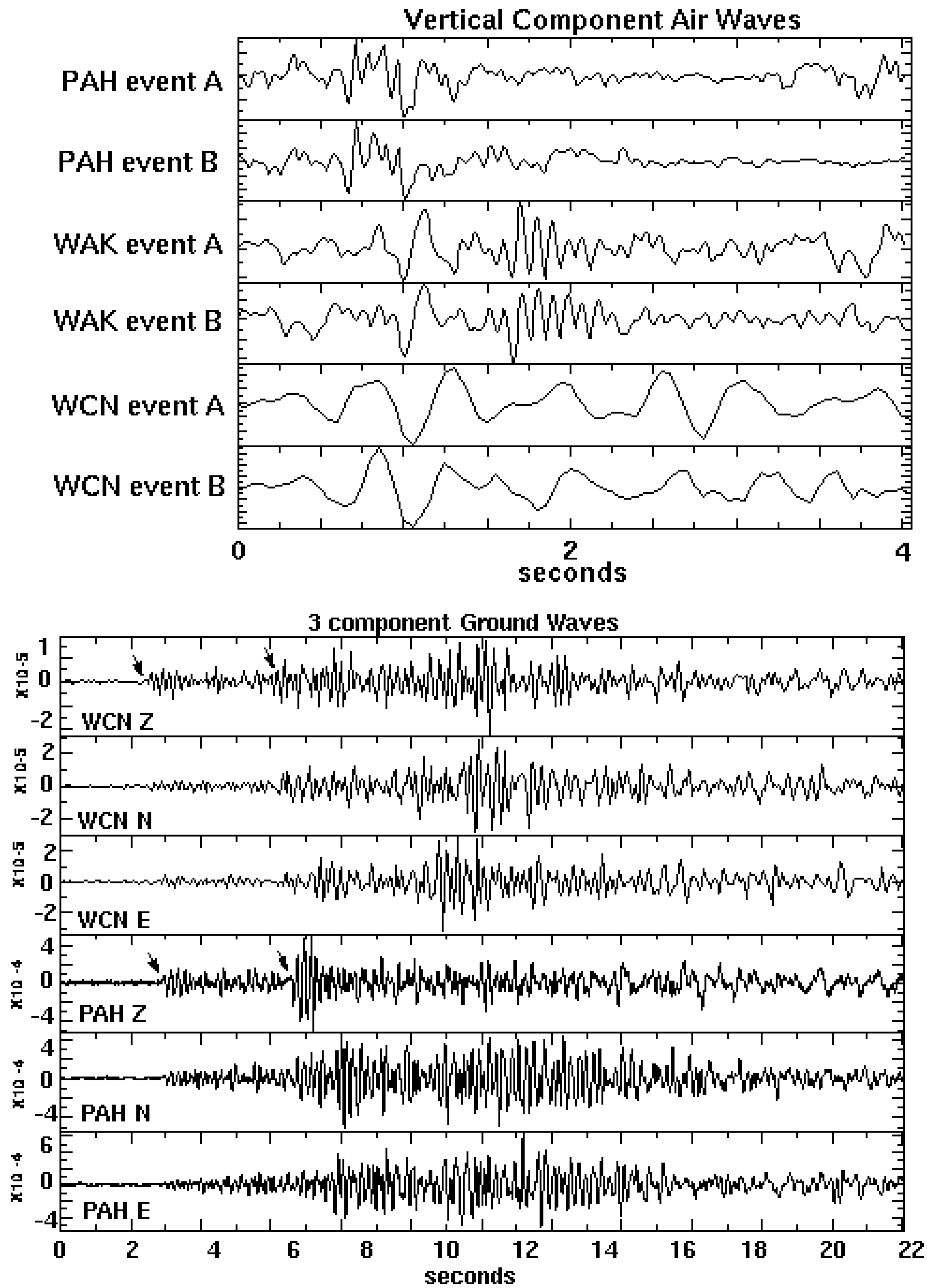


Figure 2a. Vertical component seismograms from station PAH and WCN. The P1 and P2 labels indicate P-wave arrivals for explosion A and B. N1 and N2 labels indicate the N-wave (air wave) arrivals for explosion A and B.

Figure 2b. Seismograms of low-passed filtered vertical component air waves and 3 component seismic waves used in this analysis. The arrows point to the arrival of P-wave of explosion A and B.

Figure 2b.



In their request to the Seismological Laboratory *(John Piatt, personal communication)*, the CSB reported that two explosions were separated by a horizontal distance of approximately 250 feet (76.2 meters), along a strike of 147° . Uncertainties in these measurements are due to uncertainty on where the "centers" of the explosions were located. The northern explosion occurred in a building that was formerly about 40 feet by 40 feet in dimension *(CSB, 1998)*, and the southern explosion left a kidney-shaped crater that was about 30 feet across and 50 feet long (John Piatt, personal communication). A circular approximation would have a radius of 40 feet. Based on these dimensions, the separations between the centers of the explosions could be uncertain by as much as several meters, and the azimuth could be uncertain by a few degrees. According to testimony to the CSB (John Piatt, personal communication), there were about 7500 to 8000 pounds of explosives (TNT or COMP-B) at the northern site, and about 15000 pounds of explosives (PETN) at the southern site. Based on several independent lines of evidence, the CSB has come to the conclusion that the northern explosion occurred first.

We are interested in these events because they provide the opportunity to test a cross-correlation method to estimate relative source locations. We have observed numerous cases of nearly identical seismograms called multiplets in routine monitoring activities, and have experimented with the cross-correlation of digital seismograms to estimate the spatial separation of seismic sources. By being able to actually measure the source locations on the ground, the resolving power and the errors associated with this methodology can be directly evaluated.

Analysis and Results

We located the initial explosion (explosion A) from the P-wave arrivals recorded at the UNR Keck digital stations and one helicorder record from an analog station (Table 1). The existing regional network of analog stations did not trigger on the explosion. We used the 1-D velocity model (Table 2) to estimate of the absolute location of the first explosion. Since the location determined from the P-wave arrivals of the first event is only 1.2 km from the known mapped location of the explosions, our confidence in the velocity model in Table 2 is increased.

Table 2. Velocity model used in location of explosion.

P-wave Velocity (km/s)	Depth to top of Layer (km)
3.0	0.0
4.5	1.0
5.5	2.0
6.0	4.0
6.1	7.0
6.2	12.0
6.4	18.0
6.8	28.0
7.8	38.0

To find the relative locations of explosions A and B, one requires knowing the precise time difference between the explosions, $t_b - t_a$, that can be measured from the records of P- and air-waves. We performed cross-correlations on windows of the P- and air-wave arrivals in the frequency domain *(Fremont and Malone, 1987)*. The frequency domain technique can establish finer relative time estimates that are below the limit imposed by the sampling interval. This is required for relative locations with a precision on the order of several meters. The time difference between the two explosions is proportional to the slope of the phase of the cross spectrum,

$$t_b - t_a = \frac{\phi(\delta f)}{2\pi\delta f} \qquad (1)$$

where $\phi(\delta f)$ is the phase of the cross spectrum over a frequency range delta f. The intercept is fixed at 0 Hz and a line is fit to $\phi(\delta f)$ by simple least squares. The seismogram with both explosions are windowed by 2 seconds around each of the P-wave and air-wave arrivals and then cosine tapered. The windowed seismogram of explosion A is then initially aligned by routine picking relative to the seismogram of explosion B, and the time shift from the slope of the phase of the cross spectrum is finally used to correct this initial alignment.

A measure of the coherency of the phase arrivals is used to determine the frequency range over which the slope of the cross-spectrum phase is analyzed. The normalized coherency between two time series measures the similarity of their shapes, ranging between 0, when they are completely dissimilar, to 1 when they are identical. The coherency in the frequency domain, C(f), between the Fourier transform of seismograms $s_1(f)$ and $s_2(f)$ is defined here following Menke et al. (1990),

$$C(t_b - t_a, \Delta f, f) = \frac{|< s_1^*(f) s_2(f) >|^2}{< s_1^*(f) s_1(f) >< s_2^*(f) s_2(f) >} \qquad (2)$$

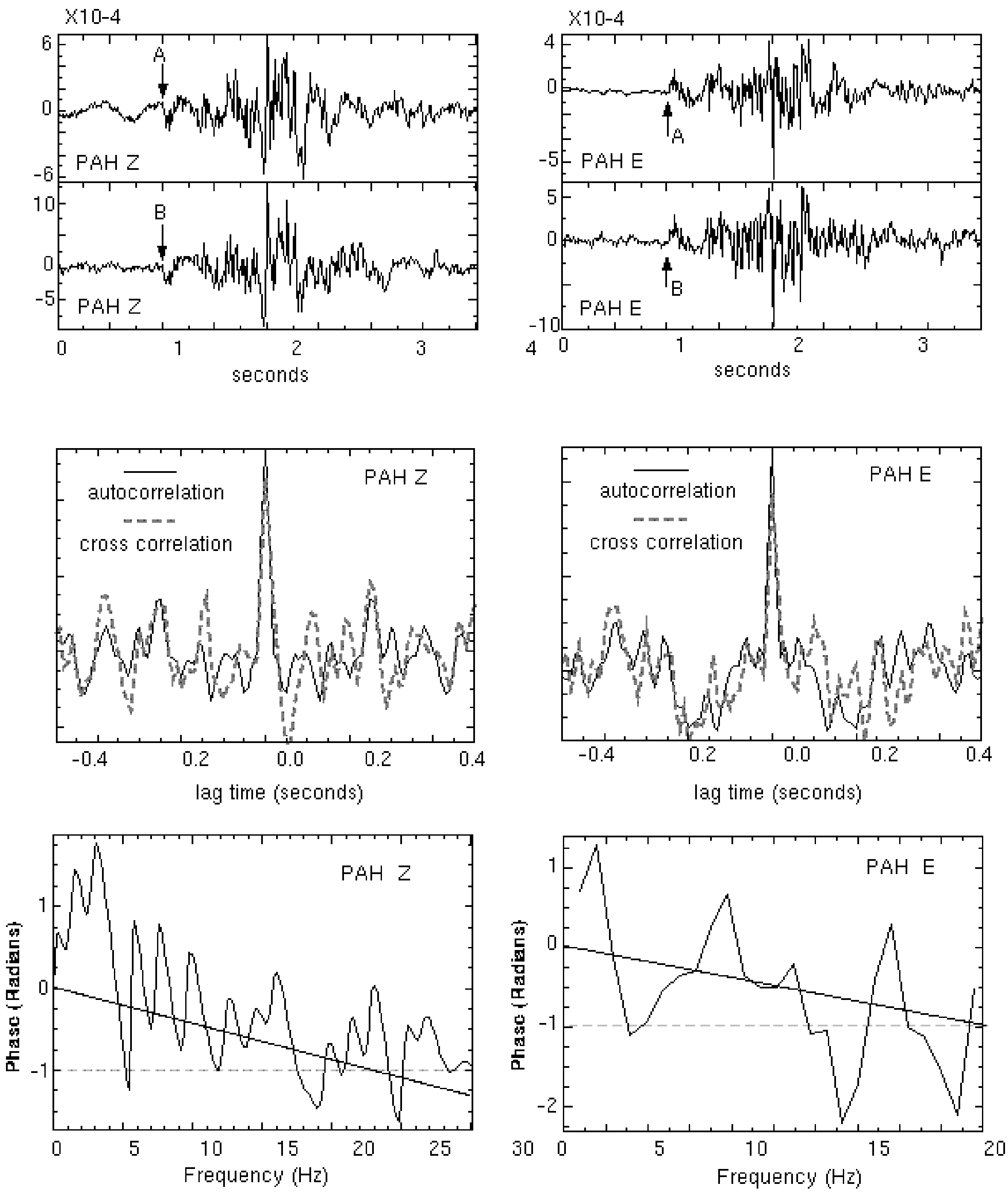
where f is frequency, < > denotes boxcar averaging over frequency interval Δf centered on f, and s* denotes complex conjugation. The windowed seismograms are shifted by $t_b - t_a$ as estimated from equation (1). We find that the coherency between phase arrivals falls-off at high frequencies, and therefore we only fit $\phi(\delta f)$ for f above 80% coherency. This fall-off is probably due to the slight difference in the travel paths from the source separation, later arrivals from the first explosion superimposed upon the record of the second, and possible differences in the details of the two source time functions. An example of the cross-correlation is shown in Figure 3, and the apparent time lags with uncertainties derived from these cross spectra are given in Table 3.

Table 3. Time after the first explosion until the maximum of the cross correlation of the first and second explosion.

Station	Component	P-wave $t_b - t_a$ (sec)	Uncertainty (ms) *	Air-Wave $t_b - t_a$ (sec)	Uncertainty (ms) *
WCN	Z	3.599	11	-	-
WCN	E	-	-	3.403	10
PAH	Z	3.582	6	3.582	9
PAH	N	-	-	3.542	-
WAK	Z	-	-	3.330	11
WAK	N	-	-	3.330	-

* **Standard Deviation of phase spectra converted to apparent time separation between explosions.**

Figure 3.

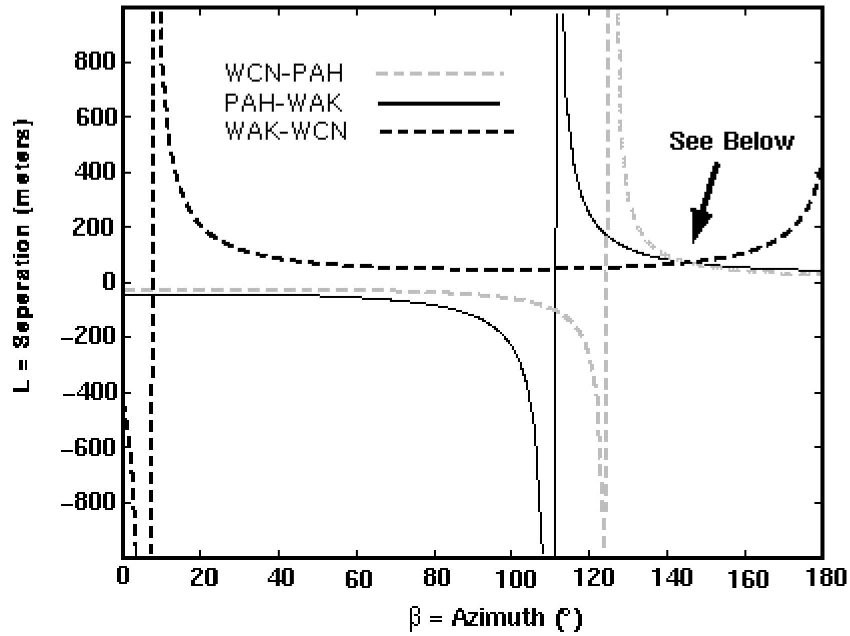


The vertical and east-west component of air-waves recorded from PAH with the cross- and auto-correlation functions. The bottom panels show the slope of the phase of the cross spectrum are fit over the frequency range of > 80% coherency.

Based on the time separations from the cross-correlations method, we estimate L, the distance separation of the second event relative to the first as a function of β, the hypothetical direction from the first source to the second, using:

$$L_{ij}(\beta) = \frac{c\ \Delta t_{ij}}{\cos(\beta - \theta_i) - \cos(\beta - \theta_j)} \qquad (3)$$

where c is either the air velocity of 343 m/s or P-wave velocity of 3000 m/s, Δt_{ij} is the difference in the times between the explosions at stations i and j, and β is the azimuth from the first explosion to the i th station. The better resolution results from an analysis of the air-wave arrivals because of the substantially slower air velocity. L_{ij} is computed from values of ranging from 0 to 180° for the 3 station pairs to find a simultaneous best solution at $\beta \approx$ 145.1° (S35°E) and L $\approx$ 73.2 meters (Figure 4). The relative location estimates based on the P- and air-waves are shown in Figure 5 along with the error estimates. The results for the air-wave unambiguously indicate that the second explosion B was southeast of the first explosion A. This result leads to the conclusion that the initial explosion was at the northern site, which is consistent with the analysis of the CSB.



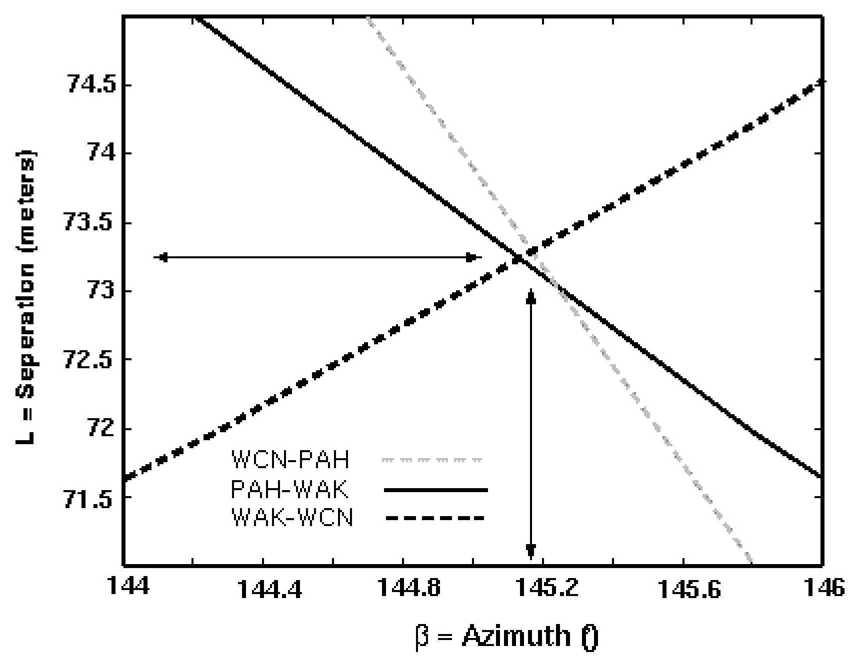


Figure 4. A plot of L, the source seperation versus β, the azimuth between sources. The arrows point to the best solution for L and β.

The relative locations based on the moveouts of these phases are, within error bars, consistent with the location of the second event based on the CSB investigation. The differences in separation between our estimate (73.2 meters) and the CSB estimate (76.2 meters) is small compared to the source dimensions, and the difference in azimuth between our estimate of S35°

E (145.1°) and the CSB estimate of S33°E (147°) is also within the range of angles that is allowed by the source sizes. The uncertainties in measuring $t_b - t_a$, shown in Table 3, corresponds to the standard deviation of $\phi(\delta f)$. This standard deviation is considered as the maximum uncertainty of determining the slope using equation (1). There is always a $2\pi n$ uncertainty in unwrapping the phase spectra but since an initial shift was performed, we expect *n* to equal around 1 and the maximum uncertainty in *n* to be less than 2π. The uncertainties in determining the slope of the cross phase spectra are then propagated through equation (3) by fixing β and using the correct polarities of the $t_b - t_a$ uncertainties. This gives the maximum uncertainty in source separation given only a pair of stations and their geometry. The importance in receiver geometry on uncertainty is shown by the difference in separation uncertainties, with ± 7 meters between PAH and WAK, which are almost along strike of the explosions, and ±21 meters between WCN and WAK, which are relatively more perpendicular to the strike. The $t_b - t_a$ uncertainties are not propagated through the simultaneous determination in L as a function of β because it is used to show the best combined estimates of these parameters.

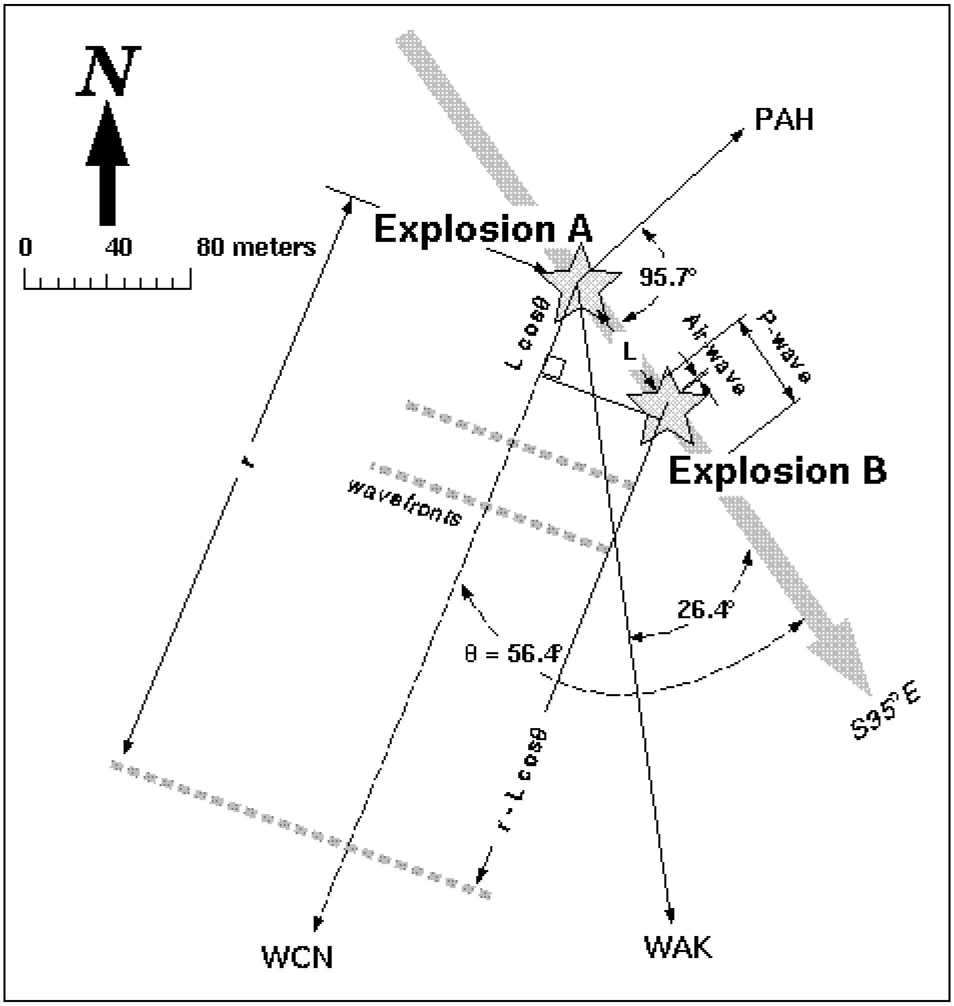


Figure 5. A Schematic map of the explosion site with likely geometry of explosions marked as "stars" and the estimated relative seperations shown as uncertainties along azmuith of S35°E. See equation (3) in text for variable definitions. The

There is no significant source of error associated with timing in the recorder itself. The digital stations maintain absolute timing by synchronizing with a GPS time signal that is broadcast from the Seismological Laboratory. The GPS signal is broadcast every second and a high precision oscillator in the seismograph unit is phase-locked to UTC by this pulse. A radio frequency delay of 44 ms, which occurs in the electronics and telemetry systems, is accounted for in establishing absolute time of the recorded waveforms. A timing mismatch of 1 msec between the GPS time and the internal clock time results in a clock correction that is reported by the instrument. Timing errors during regular operation rarely exceed several msec. Because the two explosions occurred within 3.5 sec, the absolute timing of the instrumentation is not critical, and only the error in the digitization rate is relevant. The manufacturer reports that errors in the digitization rate for the internal oscillator do not exceed 1 msec for any one sample and are expected to be on the order of 50 microsec. If the oscillator would drift more than 1 msec over any recording period, then a timing correction would be initiated by the instrument and its results would be recorded in the instrument log. For the air-wave, 1 *msec* would introduce an error of about 0.3 meters in the source location.

Atmospheric conditions that affect the speed of sound can shift the estimated separations slightly. We used an air velocity of 343 m/s *(Kinsler et al., 1982)*. For a 10% uncertainty in the assumed air velocity of 343 m/s, which is greater than expected, the relative source separation error would be ±7.0 meters, which does not impact our conclusion as to the relative source locations or chronology. A consistent wind velocity across the array on the morning of the blasts would not be significant; a 10 MPH wind is only 1.3% of the speed of the air-wave.

One of our objectives was to see if it is feasible to measure the separation between the events using the P- and S- waves. From Table 4, we see that the best estimate of the separation using the P-waves is 79.9 m, which is consistent with the estimates using the air-waves. However, the uncertainty in the time separation for the P-waves from WCN and PAH leads to a large uncertainty on the separation. The P-wave at WAK, 116 km epicentral distance, was too weak to provide a reliable separation. We consider these results to be very encouraging. With an adequate signal-to-noise ratio, the locations of closely spaced multiple events recorded at three or more stations should be resolvable.

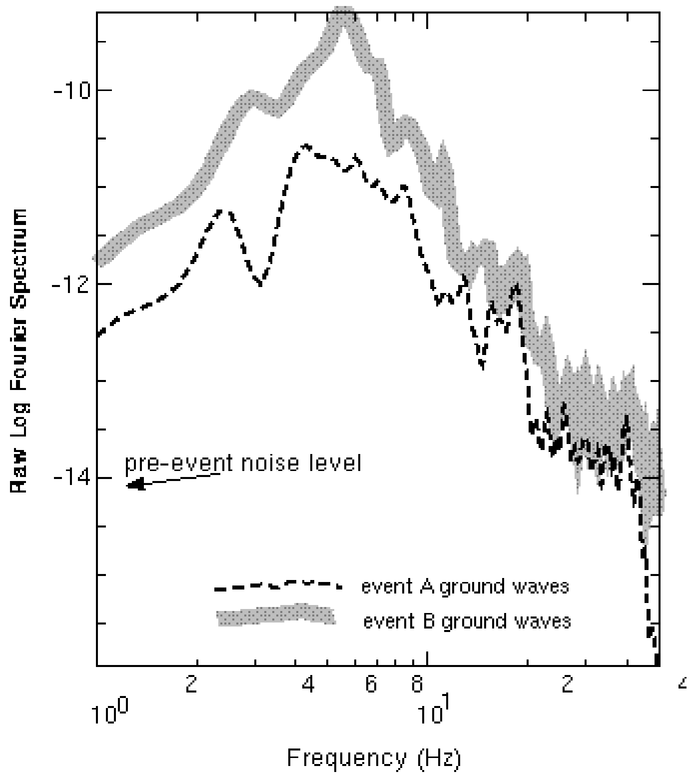
Table 4. Geometry and results of source separation estimation.

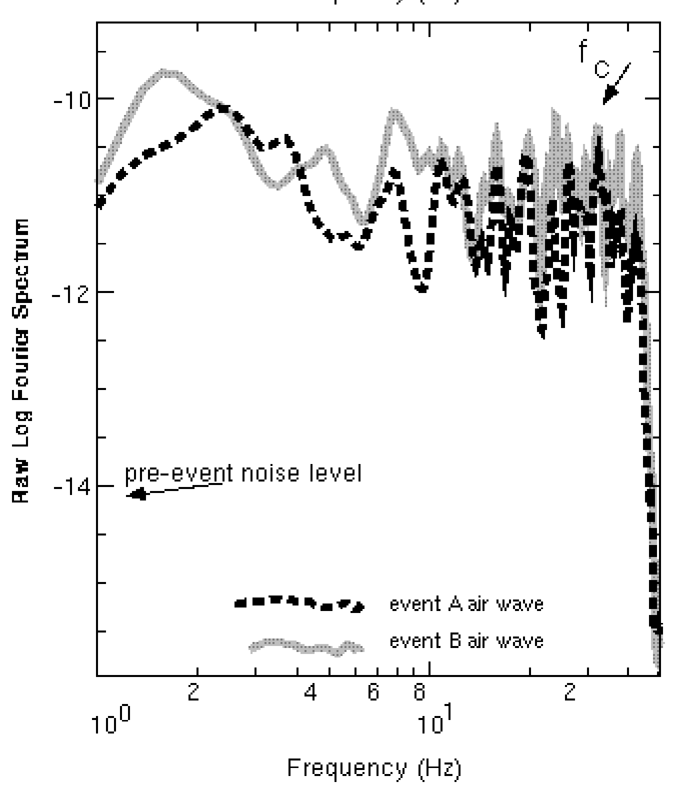
Path	P-wave (sec) *	Air-wave (sec) *	θ_j°	θ_j°	Separation (m)	Uncertainty (m)
WAK-PAH	-	**0.2126**	**-26.4**	**95.7**	**72.3**	**66.36-80.14**
WAK-WCN	-	**0.0752**	**-26.4**	**-56.4**	**73.3**	**52.12-94.20**
WCN-PAH	-	**0.1374**	**-56.4**	**95.7**	**73.2**	**63.30-83.20**
WCN-PAH	**0.0144**	-	**-56.4**	**95.7**	**79.9**	**1.8-158.0**

*** Δt_{ij} is the difference in $t_b - t_a$ between station pairs along path.**

Figure 6 shows the uncorrected spectra of the P-wave and the air-wave from the two explosions at PAH (Guralp CMG-40 velocity sensor). The three components are log averaged and then smoothed. Based on the P-wave at PAH, explosion B was 3 to 4 times larger than explosion A, consistent with reports that the second site "B" contained more explosives. The spectrum of air-waves of explosion B is only a little larger than explosion A. This may suggest that explosion B was more coupled to the ground, allowing more energy to be partitioned into the ground than into the air. The CSB hypothesized that the second explosion was triggered when debris from the first explosion crashed through the ceiling or skylight at the second site. If so, we speculate that the second explosion may have been triggered at the top of the stockpile, resulting in downward directivity and a different partitioning of energy between the ground and the air.

Figure 6. Uncorrected P-wave and air-wave





The spectral curves are the smoothed log average of the three components of motion. The arrow points to peak spectral value of a noise window before explosion A.

The physical dimensions of the explosions, like the dimensions of earthquakes, should be related to the corner frequency, fc, measured from the Fourier spectrum. To test this, we used an equation for the earthquake source radius r from Brune (1970),

$$r = \frac{2.34\,c}{2\pi f_c}, \tag{4}$$

where c is either the P-wave velocity or the speed of sound in air. The measured crater of the second explosion B was about 12 meters across and 1.8 meters deep, suggesting that = 6 meters is the expected source radius. The northern explosion A did not leave a crater, consistent with upwards rather than downwards directivity. The building was formerly 40 feet by 40 feet (CSB), giving an upper limit to the source radius of about 6 meters.

The Fourier spectra from the air-waves, in Figure 6b, are relatively flat from 1 Hz to above 30 Hz. The high frequencies of the air-waves are limited by the anti-aliasing filters in the recorder ($\approx$ 40 Hz). The spectrum from explosion A might suggest the presence of a corner at about 30 Hz, which from equation (4) would give a source radius of 4 meters. Such a result is reasonable considering the independent information about the size of the building.

The P-wave spectra fall off rapidly above 6 Hz, so we take 6 Hz to represent the corner frequency of these spectra. In equation (4) we do not have the P-wave velocity, so arbitrarily assume it to be 1000 m/sec, which we consider reasonable for weathered bedrock. With this combination of parameters, equation (4) gives $r \approx 60$ m, which is about a factor ten larger than the estimate from the air-wave and from ground observations. We therefore suggest that attenuation along the path has played a major role in decreasing the amplitude of high frequency P-waves. The P-waves spectra have decreased to amplitudes comparable to the pre-event noise above 20 Hz, implying that the attenuation eliminates the chance to use P-waves to estimate the source dimension for such small events whether earthquakes or explosions. For earthquakes, the P-waves would only need to pass through the near surface zone of severe attenuation once, so resolution of a high corner frequency should be somewhat better than in this case.

Conclusions

We have analyzed the relative arrivals of both seismic P- and air-waves at a number of seismic stations to estimate the spatial separation and orientation of two closely-spaced explosion sources that occurred within approximately 3.5 seconds. By using precise timing from the cross-correlations of the air-waves from multiple stations, and assuming an air velocity of 343 m/s, we estimate that the separation is about 73.2 meters. This accuracy results from the relatively slow velocity of the air phases. We also estimate that the two sources align along an azimuth of S35° E. The separation and orientation of the two explosions were well within uncertainties of the data provided by the CSB. The separation determined from the relative P-wave arrivals is similar, 80 meters. From the relative spectral amplitudes of P- and air-waves, we speculate that explosion B may have had a downward directivity, whereas explosion A may have been more upwardly directed. From the viewpoint of forensic seismology, this experiment was successful, in that the air-waves unambiguously demonstrate that the northern of the two explosions occurred first. We confirm that the relative separation of sources can be determined precisely using only a pair of regional seismic stations. We are encouraged that this approach can also be applied to earthquakes.

Acknowledgments

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